POST-FLIGHT ANALYSIS OF A 10 K SORPTION CRYOCOOLER

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ABSTRACT

In May 1996, the Brilliant Eyes Ten-Kelvin Sorption Cryocooler Experiment (BETSCE) was flown aboard the Space Shuttle flight STS-77 in the first space-flight demonstration of chemisorption cryocooler technology. While on orbit, BETSCE successfully met its science objectives of cooling from 70 K to 10 K in less than two minutes, sustaining a 100 mW heat load below 11 K for over ten minutes, and demonstrating recycle times of approximately eleven hours. The hydride compressors were able to circulate and compress the hydrogen refrigerant fluid in a repeatable manner with no adverse microgravity effects being observed

Since completion of the Shuttle flight, the BETSCE flight hardware was carefully inspected and a repair was made to a system valve which had developed an internal leak during flight. A series of successful cooldown cycles to below 9.5 K were completed during post-flight ground tests following repair of this valve. All observed compressor and cryostat parameters obtained in the measurements performed after flight were entirely consistent with the behavior seen in the pre-flight tests. These results verify that key functional performance of the BETSCE instrument is highly reproducible and did not degrade throughout the extensive ground tests and flight operations

INTRODUCTION

Hydrogen sorption cryocoolers utilize metal hydride sorbent beds to compress and circulate hydrogen fluid within a closed-cycle Joule-Thomson (J-T) system to provide active cooling in the 10 to 30 K temperature range. Sorption cryocoolers offer long-life, low-vibration solutions to meet the cooling needs of future instruments in astrophysics space telescopes[1,2], space superconducting electronics, and military surveillance satellites Johnson and Jones[4] recognized that a periodic 10 K sorption cryocooler permits repeated quick cooldowns from initial temperatures -65 K and low average power consumption for those applications where intermittent operation is sufficient. The 10 K periodic cryocooler concept has been thoroughly described elsewhere[3,5,6]. Briefly, metal hydride *sorbent* beds are used *to* compress hydrogen gas to a nominal pressure of 10 MPa for storage in a tank between short duration cooling periods. On command, hydrogen gas flows through an upper stage precooler at -65 K to a J-T expansion valve to form liquid hydrogen in a cryostat-reservoir with the non-condensed hydrogen gas being absorbed by a $LaNi_{4.8}Sn_{0.2}$ filled sorbent bed. Solid hydrogen at below 11 K is formed as the pressure in the J-T reservoir is reduced to -100 Pa using a second hydride sorbent bed containing ZrNi powder. The entire cooling process from 65 K to below 11 K is completed within 120 seconds and the low temperature is maintained until all the solid hydrogen has been sublimated. The recharging of the hydrogen tank from the sorbent beds takes 6 - 12 hours before the rapid cooldown can be again performed.

The Brilliant Eyes Ten-Kelvin Sorption Cryocooler Experiment (BETSCE) project was undertaken to develop a complete closed-cycle periodic 10 K sorption cryocooler suitable for demonstration in earth orbit on the Space Shuttle. The primary objectives of BETSCE were: (1) provide a thorough end-to-end characterization and performance validation of a hydride sorption cryocooler in the 10 to 30 K temperature range, (2) acquire the microgravity database needed to provide confident engineering design, scaling and optimization, (3) identify and resolve interface and integration issues, and (4) provide hardware qualification and safety verification heritage. Detailed understanding of microgravity issues associated with the heat and mass transfer processes within the sorbent beds and the separation and retention of the liquid and solid phases of hydrogen within the J-T coldhead is necessary to eliminate excessive design margins in future periodic and continuous 10 K sorption cryocoolers. The present paper provides an overview of BETSCE behavior during flight and ground testing with a final assessment of vital lessons-learned for future design and fabrication of long-life periodic and continuous 10 to 30 K sorption cryocoolers.

SYSTEM DESIGN AND OPERATION

The BETSCE instrument contains five integrated subsystems: Sorbent Bed Assembly (SBA), Cryostat Assembly (CA), Tank & Valve Assembly (TVA), Control Electronics Assembly (CEA), and the Structure Assembly (SA). The basic BETSCE operating cycle is briefly summarized in Figure 1 with the use of the fluid schematic. Since step-by-step descriptions of the cooldown-recharge cycles are available elsewhere[5,7], no additional details will be given here.

BETSCE functional ground tests[5] clearly demonstrated that all of the basic performance requirements had been exceeded by the hardware. Both the heat and mass transfer performance of the BETSCE Sorbent Bed Assembly exceeded the early predictions The Fast Absorber Sorbent Bed (FASB) was able to absorb the necessary hydrogen and dissipate the heat of reaction during the 2 minute cooldown phase while maintaining the back-pressure typically below 0.35 MPa. The Low Pressure Sorbent Bed (LPSB) demonstrated that it could solidify the hydrogen within the coldhead in less than 10 seconds and continue to maintain the coldhead at temperatures as low as 9.44 K. Additionally, the High Pressure Sorbent Bed (HPSB) repeatedly compressed hydrogen from pressures around 0.07 MPa to greater than 10 MPa.

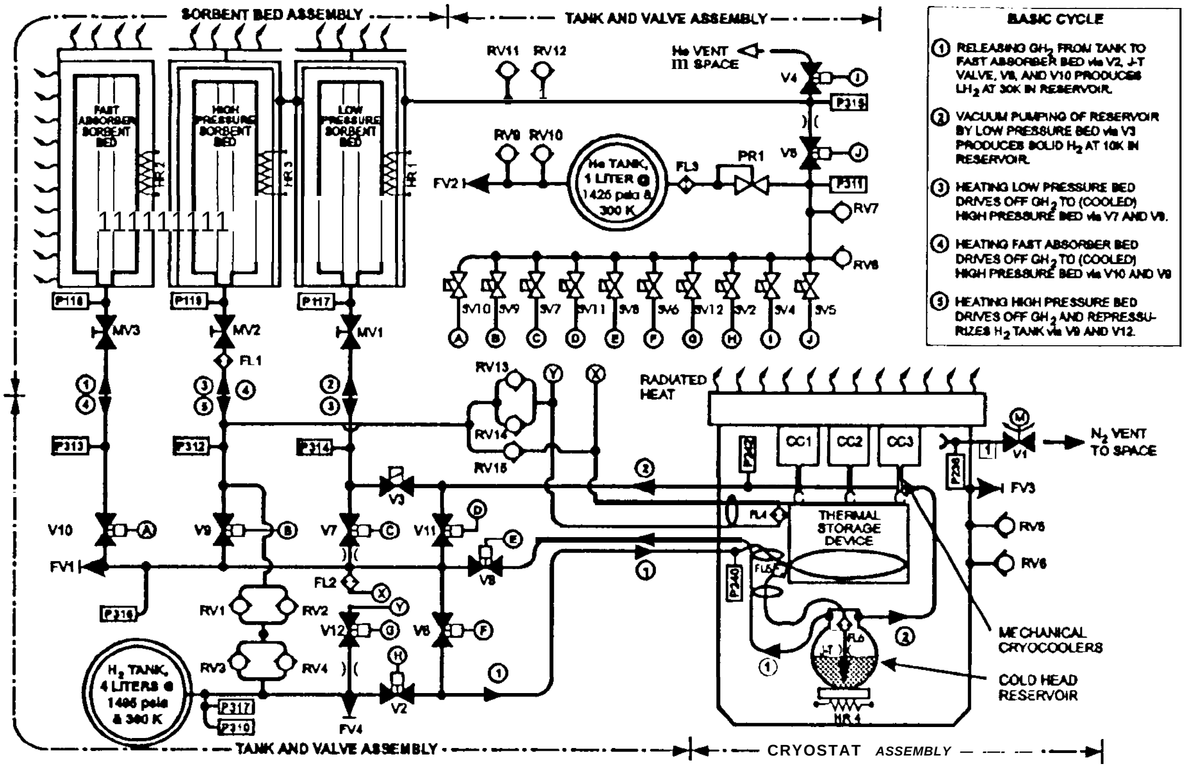

Figure 1. BETSCE fluid schematic with outline of 10 K cooldown cycle.

During initial tests, freezing of contaminants (e.g., H_20, CH_4, etc.) sometimes caused the J-T capillary tube to clog within the cryostat when cooling to -26 K, To solve this problem two custom "cold trap" adsorption filter assemblies were fabricated and installed within the hydrogen system. Both assemblies are located on the Thermal Storage Device (TSD) which is cooled to 65 - 80 K within the cryostat. These cryogenic adsorbers are constructed from 3 16L stainless steel with 2 µm porous filter discs shrink fitted and welded at each end of the devices. One adsorber assembly (identified as FL5 in Figure 1) is filled with sodium aluminosilicate molecular sieve material and is located just upstream of the cold heat exchanger and J-T valve inlet. The second cold trap (denoted FL4) contains activated Saran carbon and is located in-line between the HPSB and the hydrogen tank as shown in Figure 1. Consequently, hydrogen from the HPSB is filtered and cleaned as it flows through this cold adsorber before entering the H_2 tank during the tank recharge process. Following installation of the two adsorber cold traps, no further difficulties with contaminant gas freezing was noted during ground and flight tests.

Solid particulate also caused problems during pre-flight testing, After the second occurrence of a particulate becoming lodged within the J-T capillary tube, a custom J-T valve filter assembly was fabricated and installed to reduce the recurrence of further particulate contamination of the J-T capillary. This J-T filter assembly (denoted as FL6 in Figure 1) fully encapsulates the inlet side of the J-T valve with a shrink-fitted 2 µm porous stainless steel filter disc installed ahead of the capillary opening. No further entrapment of particulate at the J-T valve were observed during subsequent ground and flight testing.

An important objective of the BETSCE project was to make comparisons of performance parameters predicted by a transient thermal simulation mode1[7] with experimental data from ground tests. In support of this objective, a series of 10 K cooldown

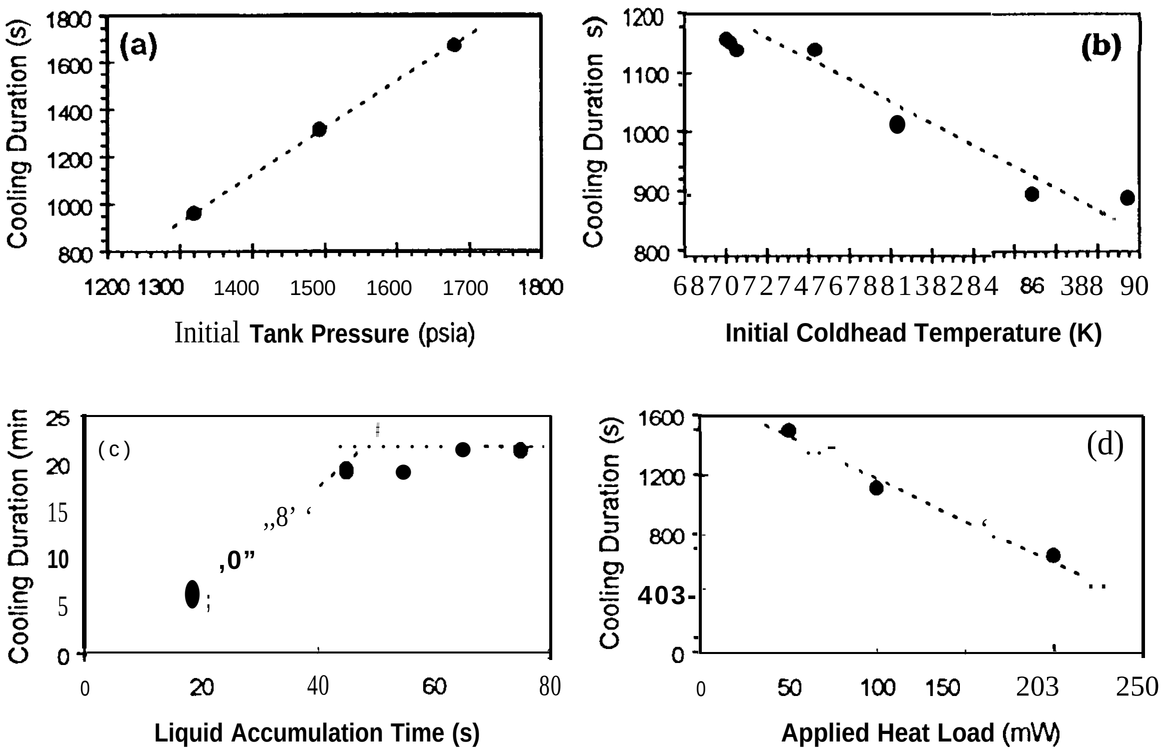

Figure 2. Impact of (a) initial tank pressure, (b) initial coldhead temperature, (c) liquid hydrogen accumulation time, and (d) applied I^2R heat load on the coldhead cooling duration below 11 K.

experiments was conducted to assess the impact of several parameters on low temperature cooling duration. These results are summarized in Figure 2. In accordance with thermal model simulations, the cooling duration below 11 K was observed to increase with tank pressure and liquid hydrogen accumulation time, while these times decreased as the initial coldhead temperature and applied heat load increased. The minimum coldhead temperature was found not to be sensitive to these parameters (i. e., 9.4 K $< T_{min} <$ 9.5 K) except for heater input power where T_{min} rose to 9.8 K at 200 mW. These tests also showed the cooldown time to increase with rising initial coldhead temperature and to decrease with rising tank pressure, which corresponded to trends predicted by the model simulations.

In summary, the pre-flight ground tests confirmed that BETSCE exceeded all performance requirements, was capable of cyclic operation with reproducible cooldown temperatures and duration, and satisfied all Shuttle safety and interface requirements.

IN-FLIGHT PERFORMANCE

The BETSCE instrument was launched into orbit on Shuttle Mission STS-77 (Orbiter Endeavour) on May 19, 1996 with BETSCE mounted on the Shuttle orbiter payload bay side-wall. Waste heat from BETSCE radiated to space by flat plate passive radiators oriented out (+Z) of the Shuttle bay. In order to begin cycling operations, BETSCE initially completed preconditioning sequences that cooled the TSD to -65 K and then desorbed the hydride sorbent beds to pressurize the hydrogen tank. As recently reported[8], the sorbent beds successfully brought the H_2 storage tank to an operating pressure of 9.8 MPa within 24 hours after the TSD had cooled below 70 K. These results demonstrate that the sorbent beds were able to effectively compress hydrogen to identical pressures as had been

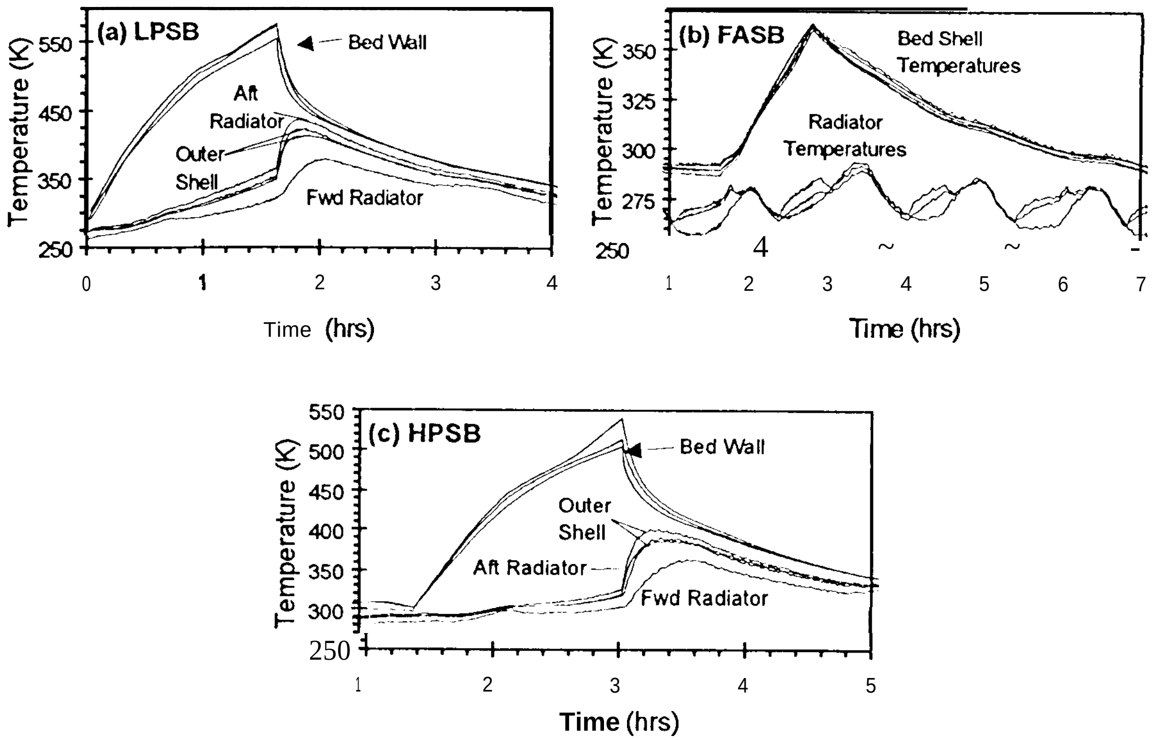

Figure 3. Temperature profiles of sorbent beds during on-orbit desorption and cooldown: (a) Low Pressure Sorbent Bed, (b) Fast Absorber Sorbent Bed, (c) High Pressure Sorbent Bed,

achieved in ground tests. Temperature profiles of the bed walls, outer shells, and radiators for the individual sorbent beds during their resorption heating-cooling steps are presented in Figure 3.

Although bed temperatures during heating in orbit were very similar to behavior found in ground testing[5], the rates of cooling were slower and the outer shell and radiators were hotter (e.g., peak temperatures greater by -25 K and -50 K for LPSB and HPSB, respectively) during flight. Both of these effects are attributed to the fact that beds were in vacuum during earth orbit which restricted heat transfer from the beds to the flight radiators. In contrast, the bodies and shell structures of the sorbent beds also lost heat via natural convection with the ambient air during ground tests, thus providing further cooling. Temperature oscillations due to Shuttle orbiter attitude changes and -90 minute day-night cycles during earth orbit are quite distinct for the FASB radiator temperatures shown in Figure 3b. These cyclic fluctuations are less apparent in Figure 3a and 3c, but are also present for the LPSB and HPSB radiators.

Figure 4 shows the initial on-orbit 10 K cooldown for BETSCE. The cooldown from 70 K to 11 K was completed in under 2 minutes, and a 100 mW I*R heat load was sustained at below 11 K for 10 minutes, thus meeting the primary system performance objectives[3] for the BETSCE flight. After the cooldown was completed valve V2, which isolates the tank from the cryostat, did not reseal properly. This allowed hydrogen to leak from the tank to the cryostats.

Although the problem with valve V2 was to prevent additional 10 K cooldown cycles, valve control sequences were modified to allow continued cycling of the metal hydride compressors and BETSCE was able to produce liquid hydrogen. The coldest temperature

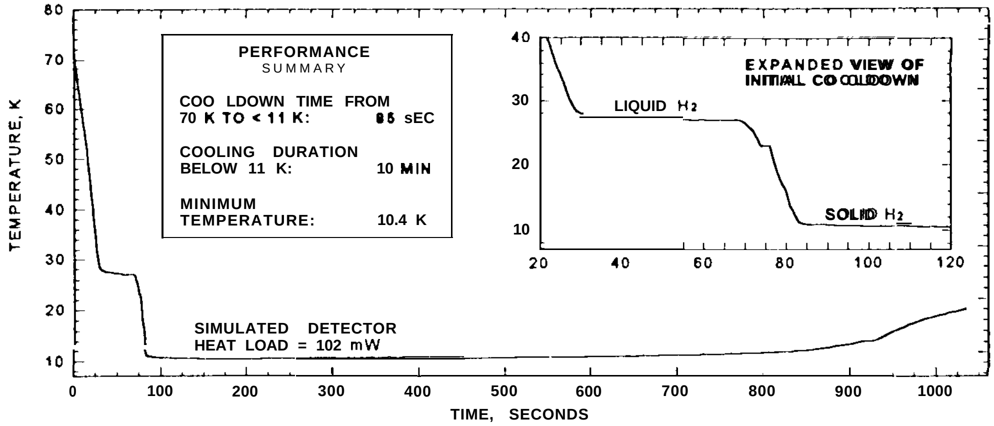

Figure 4. Summary of on-orbit 10 K cooldown.

achieved in these cycles was 18.4 K and the longest cooling duration was over 32 minutes. A total of eight liquid hydrogen cycles were achieved by the end of the mission[8]. The temperatures recorded during the initial hydrogen absorption by the FASB in these cooldowns confirmed that melting of the phase change material n-hexadecane while in microgravity remained capable of absorbing much of the heat released by the hydriding process[3,5,7].

POST-FLIGHT EVALUATIONS

After the return of the BETSCE hardware to JPL, the first activity was to disassemble the leaking valve V2 for inspection. A microscopic examination of the valve seat revealed numerous metallic particles embedded in the sealing groove. While the specific sources of these particulate cannot be established with any certainty, their most probable origin is fabrication debris trapped in the 4-liter hydrogen storage tank or associated TVA plumbing. Although efforts were made to clean and rinse this vessel prior to welding it into the hydrogen manifold, the small (i.e., 0.46 cm) opening to the connecting tubing impedes not only removal of residual particulate but also permits entrapment of any particles generated during later assembly procedures. For ground tests in any orientation of the BETSCE system, the particles would remain trapped in the bottom of the tank. Since these particulate would be floating in the tank while in orbit, they were apparently swept out of the tank and lines towards the valve during the nominal 70 sL/min flow rate for the cooldown and liquid hydrogen accumulation steps of the first 10 K flight cooldown. After determination of the presence of particles on the removed valve stern, valve V2 was thoroughly cleaned and a new valve stem/seat was installed. Subsequent vacuum and pressure leak checks confirmed that the integrity of valve V2 had been restored and it was sealing properly when closed.

In order to establish whether the BETSCE hardware had retained its performance capabilities after flight operation and repair of the valve V2, a series of the ground tests were conducted. No contamination or clogging effects were seen in fifteen 10 K cooldown cycles. The minimum coldhead temperatures were consistently between 9.45 and 9.50 K with cold duration periods > 1100 seconds and all other sorbent bed properties during cooldown and recharging were nearly identical to the pre-flight ground test results. Figure 5 compares six post-flight 10 K cooldowns to a representative pre-flight run under slightly different test conditions. These results verified that no substantive alteration in cooldown performance remained after the Shuttle flight and subsequent repair of valve V2. No permanent damage from the particles, which had limited on-orbit testing, was detected with the other BETSCE valves or J-T components during post flight testing.

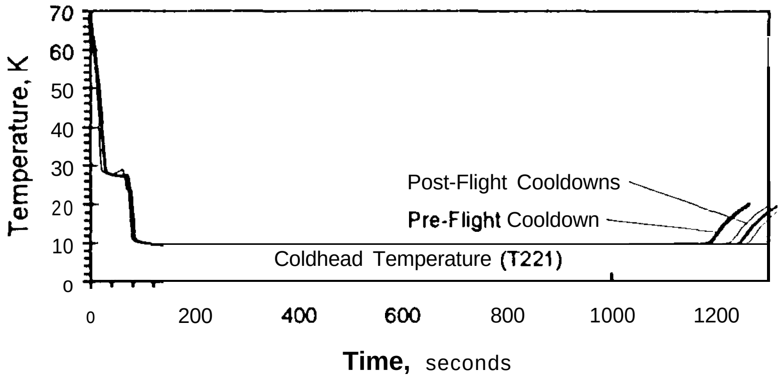

Figure S. Comparison of several post-flight 10 K cooldown cycles to a pre-flight test.

Over 130 periodic 10 K cooldown-recharge cycles were made with the BETSCE hardware during the ground tests in addition to the flight experiments performed aboard the Shuttle. No degradation in the storage capacities and reaction kinetics for the hydride sorbent beds was observed up through the final post-flight ground tests. All components in the cryostat, including the Stirling cryocoolers, TSD, heat exchangers, and J-T reservoir functioned appropriately during the tests. The temperature and pressure sensors performed well and the TVA valves operated dependably (except for the leaking of V2 during flight from particle contamination).

LESSONS LEARNED

Future Design Improvements

Based on the BETSCE hardware development experience and analysis of the BETSCE ground and flight test results, a number of valuable lessons-learned can be applied to improve the design of future operational 10 K sorption cryocooler systems[1,2]. First, it is important to recognize that the size and weight of a 10 K cryocooler can be greatly reduced from that of BETSCE. The BETSCE instrument was essentially an adaptable test bed that allows extensive characterization testing of an experimental 10 K sorption cryocooler system within the highly constrained Shuttle safety and interface requirements. Hence, only nominal efforts were made to minimize the size, weight, or power requirement, as the BETSCE resources were focused on developing the important new technology elements of the system, particularly those that needed to be validated in microgravity. As described in References 5 and 9, an operational periodic 10 K sorption cryocooler should be achievable with a mass of --30 kg including an upper stage 60 K mechanical cooler.

Contamination Control Issues

For a long-life flight cooler it is necessary to completely eliminate the contamination problems encountered by BETSCE. It is crucial that the system be designed to minimize virtual leaks that trap contaminant gases internal to the gas system. Electropolished tubing and fittings should be used wherever possible, and use of organic materials (e.g. in valve seats) should be minimized. Welds are preferred to braze joints to minimize flux contaminants and trapped volumes. Although it was constructed of electropolished 3 16L stainless steel tubing, and carefully cleaned and verified to aerospace industry standards, the BETSCE hydrogen storage tank had a single 0.46 cm id. opening serving as inlet and outlet to the 4L volume. For future systems, it is recommended that all tanks contain both an inlet and an outlet to aid in more effective cleaning. It is important to pay special attention to filter manufacturing processes and cleaning procedures, especially for the filters contained within sorbent beds. These filters have very large surface areas that can trap adsorbed contaminants, and should be subjected to numerous fill/ flush and vacuum bake-outs prior to loading of sorbent material. In-line filters should be included to protect all valves and the J-T refrigeration loop from solid particulate. Detailed examination of the disassembled BETSCE valve V2 has confirmed that the leakage was caused by metallic particulate which were able to flow from the tank, fittings or plumbing only while in the microgravity conditions of flight. It should be noted that no problems with clogging of the J-T capillary line were encountered during flight or post flight ground tests. While it is likely that in microgravity conditions some particles reached the J-T inlet, this region was presumably protected by the J-T filter assembly FL6. Finally, to further reduce the risk of clogging, in-line cold trap getters should be installed to continually remove gas phase contaminants that may be generated in the closed-cycle cooler.

SUMMARY AND CONCLUSIONS

BETSCE achieved its original flight objectives. It demonstrated the ability to cooldown and produce solid hydrogen at 10 K in under 2 minutes on its first cooldown attempt on orbit while sustaining a simulated I*R detector heat load of 100 mW for 10 minutes, the ability to repeatedly produce liquid hydrogen below 19 K, and the ability to repeatedly recycle the sorption compressors. Microgravity operation was found to have no adverse effect on the ability to retain liquid and solid hydrogen, and the sorption compressors demonstrated similar heat and mass transfer characteristics as determined in ground testings. The successful BETSCE space and ground test results have validated many critical technologies for both periodic and continuous configurations of hydride sorption coolers. The end-to-end characterization and the quantitative microgravity database should enable early insertion of 10 to 30 K sorption cryocooler technology into future long-life, low-vibration, space remote sensing missions.

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